D-BAUG Workshop on Natural Hazards

Programme & Abstracts

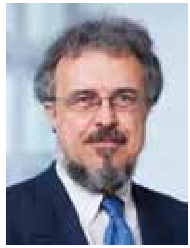
Thursday, 08 June 2017
ETH Hönggerberg, HCI J3

Department of Civil, Environmental and Geomatic Engineering (D-BAUG)

Preface

Thomas Vogel

Head of the Department of Civil, Environmental and Geomatic Engineering, ETH Zurich



As head of the Department of Civil, Environmental and Geomatic Engineering (D-BAUG), it is a pleasure for me to introduce the Workshop on Natural Hazards, held on 08 June 2017.

It is the third one of its kind after "Computationally Based Engineering Research" in June 2013 and "Monitoring and Modelling for Real-Time Control and Intervention" in February 2015.

With these workshops, D-BAUG wants to identify the potential of cooperation in topics involving all engineering and natural sciences covered by our department.

We do this by inviting international peers in the respective field and mobilizing our own experts who sometimes need a trigger or at least a good occasion to share their ideas and achievements with colleagues next door.

Natural hazards is a topic where our department has many broad competences. We cover all kinds of hazards, we try to understand the triggering conditions, we can model the events and their consequences and we are able to propose mitigation measures. It must be said, however, that we do not build effectively on past efforts. Younger colleagues do not even know that a "Research Network on Natural Hazards" (HazNETH) once existed and the MAS course "Natural Hazards Management" was completed only once. This did not happen because the topic lost actuality or importance but because the key persons involved took over other responsibilities.

It is an urgent need for D-BAUG but also for ETH Zurich, that an entity, a network, or a competence centre nails its colours to the mast.

Natural hazards need a home base at ETH, it might be as well in the Department of Environmental System Science (D-USYS) or in the Department of Earth Sciences (D-ERDW) but if engineering issues, i.e. problem solving is in the focus, we should take the lead and cannot abstain.

Let us use this workshop as a starting point of joining forces to make natural hazards more visible again at ETH Zurich as well as within D-BAUG.

I thank the organizing committee for the efforts they have taken to organize this workshop and everything around that is necessary for success.

Morning Programme

Introduction

08:30-08:35	**Prof. Thomas Vogel** (Head of department D-BAUG) *Introduction*	
08:35-08:45	**Prof. Sarah Springman** (Rector of ETH Zurich) *Welcoming address*	

Session 1 - Landslides and Earthquakes

08:45-09:30	**Prof. Eduardo Alonso** (Politechnical University of Catalonia - Invited) *Modelling fast landslides: the case of Vaiont*	*p. 4*
09:30-09:45	**Prof. Alexander Puzrin** (IGT) *Submarine landslides: unifying shear band propagation approach*	*p. 7*
09:45-10:00	**Dr. Helge Fuchs** (VAW) *Impulse waves generated by granular submarine slides*	*p. 10*
10:00-10:15	**Philipp W. Oberender** (IGT) *Observation guided constitutive modelling for creeping landslides*	*p. 13*
10:15-10:40	Coffee Break	
10:40-10:55	**Prof. Božidar Stojadinović** (IBK) *Earthquake (and natural hazard) resilience of communities*	*p. 16*
10:55-11:10	**Dr. Marco Broccardo** (IBK) *Uncertainties in seismic hazard and risk analyses: the good, the bad and the way ahead*	*p. 18*
11:10-11:25	**Prof. Markus Rothacher** (IGP) *Contributions of GNSS to earthquake hazard monitoring and assessment*	*p. 21*
11:25-11:40	**Prof. Alain Geiger** (IGP) *Determination of tectonic and landslide strain patterns from geodetic deformation observation and analysis*	*p. 23*
11:40-11:55	**Daisy Lucas** (IGT) *Study of the seasonal response of a steep scree slope in the Swiss Alps*	*p. 25*
11:55-12:10	**Prof. Jan Carmeliet** (ITA/D-BAUG) *3D DEM study of stick-slip in granular fault gouge; effect of vibration and fluid saturation*	*p. 28*
12:10-12:25	Summary panel on landslides and earthquakes	
12:25-13:30	Lunch at Food Market; Building HPH/HPR	

Afternoon Programme

Session 2 - Floods and Cryosphere-related Hazards

13:30-14:00	**Prof. Günter Blöschl** (Technical University Vienna - Invited) *Understanding flood regime changes in Europe*	*p. 4*
14:00-14:15	**Prof. Bryan T. Adey** (IBI) *Challenges in assessing road related risk to plan risk-reducing interventions*	*p. 31*
14:15-14:30	**Dr. João P. Leitão** (IfU/Eawag) *The potential of new data sources to improve urban flood modelling*	*p. 33*
14:30-14:45	**Elena Leonarduzzi** (IfU) *Forecast and warning concept for landslides in Switzerland based on rainfall triggering thresholds and multiscale hydrological modelling*	*p. 36*
14:45-15:00	**Samuel J. Peter** (VAW) *GPU accelerated BASEMENT enabling Monte-Carlo simulations for flood risk analysis*	*p. 39*
15:00-15:25	Coffee Break	
15:25-15:55	**Prof. Michael Krautblatter** (Technical University of Munich - Invited) *Destabilization of permafrost slopes: Mechanical modelling approaches and application to high-alpine infrastructure*	*p. 5*
15:55-16:10	**Prof. Andreas Wieser** (IGP) *Terrestrial remote sensing of glaciers using laser scanning and radar interferometry*	*p. 41*
16:10-16:25	**Fabian Lindner** (VAW) *Seismic monitoring of the 2016 outburst flood of Lac des Faverges on Glacier de la Plaine Morte*	*p. 44*
16:25-16:40	**Ana Stritih** (IRL) *Quantifying avalanche protection in forests using remote sensing*	*p. 46*
16:40-16:55	Summary panel on floods and cryosphere-related hazards	

Conclusion

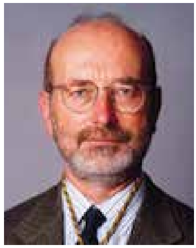
16:55-17:10	Conclusions and end of workshop
17:10	Apéro

Invited Speakers

Modelling fast landslides: the case of Vaiont

Eduardo Alonso

Politechnical University of Catalonia, Barcelona, Spain

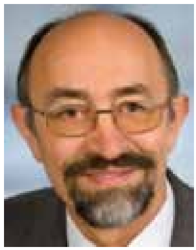


Eduardo Alonso is Professor of Geotechnical Engineering at Universidad Politécnica de Catalunya, in Barcelona, Spain. His main topics of interest are reliability and risk in geotechnical engineering, behavior of partially saturated soils, expansive soils and rocks, numerical analysis of geotechnical problems, field measurements and geotechnical back analysis, as well as slope stability. Prof. Alonso is the present Honorary Editor of the Geotechnique journal and was awarded a number of recognitions including, among others, the Thomas Telford Medal (twice), the Geotechnical Research Medal (also twice), the Crampton Prize, and the 30th Rocha Lecture. In 2017 he delivered the prestigious Rankine Lecture.

Understanding flood regime changes in Europe

Günter Blöschl

Technical University Vienna, Austria



Günter Blöschl is Head of the Institute of Hydraulic Engineering and Water Resources Management, Director of the Centre for Water Resource Systems of the Vienna University of Technology, as well as Chair of the Vienna Doctoral Programme on Water Resource Systems. His research activities include hydrological modelling across scales, flow and transport processes, forecasting of floods and droughts, analysis of climate change impacts, and socio-hydrology. Prof. Blöschl has received numerous honours including the election as a Fellow of the American Geophysical Union, the German Academy of Science and Engineering, and the International Water Academy. Recently he was awarded the Advanced Grant of the European Research Council (ERC). Prof. Blöschl was President of the European Geosciences Union (2013-2015) and is currently President-Elect of the International Association of Hydrological Sciences IAHS.

Destabilization of permafrost slopes: Mechanical modelling approaches and application to high-alpine infrastructure

Michael Krautblatter

Technical University of Munich, Germany

Michael Krautblatter is head of the Landslides Group at the Technical University of Munich. His research focuses on the non-invasive quantification and monitoring of permafrost in unstable rock and soil slopes, the quantification of magnitude, frequency and interconnectivity of landslides, and the anticipation of landslides based on thresholds, mechanical models and an understanding of the systems involved. Theory, field, laboratory and modelling based research is currently being performed within the framework of international projects in the Alps and in Arctic environments. Prof. Krautblatter has served as the chair of GAPHAZ (Glacier and Permafrost Hazards in Mountains) - a scientific standing group of both the International Association of Cryospheric Sciences and the International Permafrost Association.

Sessions

Session 1: Landslides and earthquakes

Creeping landslides are an important geohazard in Switzerland, where not only roads and bridges but also entire villages have been built on a slowly moving ground. Assessment of this hazard requires solutions of a spectrum of challenging geotechnical problems, such as landslide evolution under both regular and extreme environmental and seismic conditions; landslide-structure interaction; and effects of mitigation measures. Another relevant hazard is a seismically triggered rapid collapse of sediment slopes in lakes (both natural and artificial), potentially resulting in waves damaging coastal environments.

Despite earthquake hazard being relatively low in Switzerland, earthquake risk is rather high and it is growing. In fact, much of the Swiss built inventory was designed with little or no consideration of earthquake loads, making it, on average, more vulnerable. More consequential is the growth of the population and the businesses that use this built inventory and enlarge the wealth of the country. The recent searches for new energy sources further complicate addressing the earthquake risk.

This session presents recent advances in the analysis of dynamic evolution of terrestrial and submarine landslides, as well as in the modelling and assessment of earthquake risk. Risk problems will be framed and potential solutions ranging from structural and geotechnical interventions to approaches involving public policy, urban planning, and the insurance industry will be explored.

Session 2: Floods and cryosphere-related hazards

Flooding is one of the most damaging natural hazards worldwide, affecting large rivers as well as small Alpine streams. Important basic and applied research challenges lie in the prediction and forecasting of floods, flood risk assessment, flood management including floodplain planning, and attributing change in flood frequency and peak magnitudes. A broader perspective includes secondary hazards associated with flooding, e.g. high sediment transport, bed and bank erosion, or river morphological change.

Cryosphere-related hazards, on the other hand, can arise from snow and glacier avalanches, from the destabilisation of frozen debris slopes, the outburst of glacier lakes, or the degradation of permafrost. Such hazards are particularly relevant in the Alps, in which the density of both population and infrastructure is high. Open questions relate to the prediction of future evolution as response to climatic change, as well as interactions with other extreme events such as heavy precipitation or earthquakes. For remote areas, also the detection and monitoring of the related processes can be challenging.

This session presents contributions related to flooding and cryosphere-related hazards, and collects examples from the domains of numerical modelling, risk assessment, data analysis, and direct and remote observations.

Submarine landslides: unifying shear band propagation approach

Alexander M. Puzrin [1], Balz Friedli [1]

[1] Institute for Geotechnical Engineering (IGT), ETH Zurich

A Geographical Informational System (GIS)-based deterministic and probabilistic slope stability analysis (PSSA) for offshore developments requires slope stability calculations to be repeated millions of times, excluding possible use of finite element methods and relying mainly on analytical limiting equilibrium (LE) slope failure criteria. In strain softening soils, however, LE approach assumes that the failure takes place simultaneously along the portion of the sliding surface where the shear stress exceeds the peak shear strength. It cannot explain the failure of the parts of the slope, where the shear stress is lower than the peak shear strength, frequently observed in gigantic submarine landslides. It also cannot distinguish between different landslide failure modes, such as slab failures, spreadings, ploughings and runouts (Figure 1). There is a clear need in an alternative approach, which would allow for overcoming this limitation while maintaining the simplicity of the LE analysis.

A potential candidate to fill this gap is the shear band propagation (SBP) approach (e.g., Palmer and Rice, 1973; Puzrin and Germanovich, 2005), which in contrast to the LE provides criteria for an initial slip surface, in which the shear stress exceeds the peak shear strength, to propagate into "quasi-stable" portions of the slope, where the gravitational shear stress τg is lower than the peak shear strength τp but exceeds the residual strength τr. This helps to explain enormous dimensions of some submarine landslides in the nature. In spite of the significant effort devoted to the SBP approach in the last 10 years, its application to the practical slope stability analysis has remained challenging for the following reasons:

- a lack of confidence in this approach due to insufficient experimental and numerical validation of the phenomena of a shear band propagation in a slope and of the corresponding analytical criteria;
- infinite slope assumption: for regional triggers, such as earthquakes or sedimentation, which cause a practically uniform loading of the slope, it is not clear why only a portion of a uniform infinite slopes is weakened;
- focusing mainly on unstable (catastrophic) shear band propagating into

the "quasi-stable" parts of the slope, not considering the possibility for propagation of the shear band into the "stable" parts of the slope where driving forces are smaller than the residual strength, causing spreading, ploughing and run-out (Figure 1a);

- concentrating mainly on criteria for the initiation of the catastrophic SBP, with little attention paid to the process of its dynamic propagation and conditions for its arresting, which define the final dimensions of the affected slope length and of the resulting landslide.

Puzrin et al (2016) proposed a novel approach to modelling different stages of the submarine landslide evolution as a single continuous process driven by catastrophic and progressive shear band propagation, summarizing the recent advances in the SBP approach addressing the existing limitations, and providing analytical criteria for the shear band propagation and arrest in a 2D slope geometry. These simple criteria, validated against physical model experiments, numerical analysis and paleo-landslide data, allowed for the SBP approach to be incorporated into GIS based deterministic and probabilistic slope stability analysis, confirming the non-conservative nature of limiting equilibrium calculations.

For 2D and 3D slope geometry, Puzrin et al (2016) proposed to treat the submarine landslide evolution as a continuous sequence of catastrophic and progressive SBP mechanisms (Figure 1b). Conventional slope stability analysis assumes that slopes fail simultaneously along their entire length. In contrast, the SBP mechanism is capable of explaining the failure evolution from a relatively short initial shear band, triggered (e.g., by an earthquake) in the

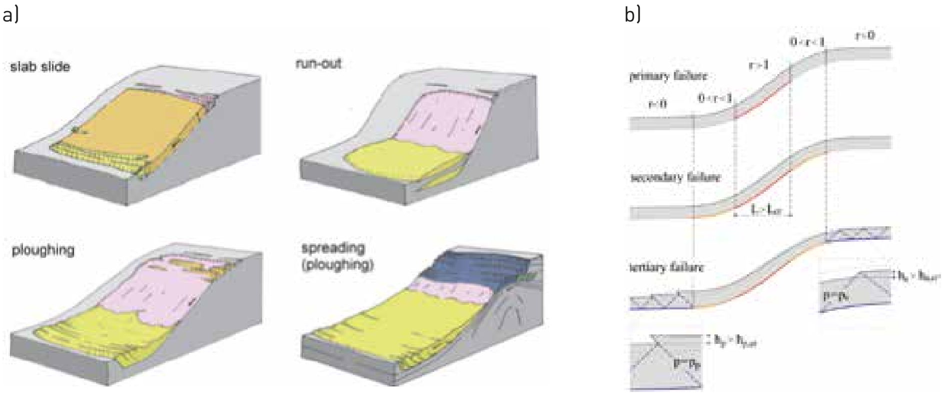


Figure 1: Submarine landslides: (a) typical failure modes in translational (courtesy of Dr. Andy Mills); (b) shear band propagation mechanisms of landslide evolution.

steepest part of the slope, where gravitational τ_g and seismic τ_h forces exceed the peak shear strength (shear stress ratio $r = (\tau_g + \tau_h - \tau_r) / (\tau_p - \tau_r) > 1$, primary failure in Figure 1b). If this initial shear band becomes sufficiently long, it can propagate catastrophically parallel to the slope surface into those parts of the slope, where gravitational and seismic forces exceed the residual shear strength ($0 < r < 1$), triggering a slab failure (secondary failure in Figure 1b). Once the slab fails in active or passive failure at its ends, this causes changes in the seabed level, driving progressive propagation of the shear band into those parts of the slope where gravitational and seismic forces are smaller than the residual shear strength ($r < 0$) and triggering spreadings, ploughings and runouts (tertiary failure in Figure 1b).

Puzrin et al (2016) demonstrated the ability of the SBP approach to formulate quantitative criteria for these post-failure evolution scenarios in Figures 1a and 1b and to explain the dimensions of some large submarine palaeo-landslides and the resulting geomorphological features. Rushton et al. (2015) incorporated the SBP approach, into the GIS based deterministic and probabilistic stability analysis and applied it to an area of the Caspian seafloor. The resulting annual probability of failure predicted by the SBP approach is an order of magnitude higher than the one predicted by the LE approach, approaching the observed historical landslide frequencies and contributing to the landslide risk assessment.

References:

Palmer, A. C., and J. R. Rice (1973). The Growth of Slip Surfaces in the Progressive Failure of Overconsolidated Clay, Proceedings of the Royal Society of London, A 332, 527-548.

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Rushton, D., Gray, T.E., Puzrin, A.M., and Hill, A.J. (2015) GIS-Based Probabilistic Slope Stability Assessment Using Shear Band Propagation. In Offshore Technology Conference 2015, Houston, USA: paper OTC 25871-MS.

Impulse waves generated by granular submarine slides

Helge Fuchs [1], Frederic M. Evers [1], Robert M. Boes [1]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich

Impulse waves, also referred to as lake tsunamis, are triggered by various mass-movement mechanisms, such as landslides, rockfalls, avalanches or glacier calvings. With the usually short propagation distances within mountain lakes or reservoirs, the wave attenuation is small, resulting in a high damage potential at the surrounding shoreline. At lakes, damages are expected for the shore vegetation or possible infrastructure. In presence of a reservoir, potential dam overtopping could lead to downstream damages due to (a) direct wave impact, (b) float impact, (c) deposited float and debris or even (d) partial or complete dam failure. According to Swiss national guidelines for dam safety, the consequences of potential impulse wave events need to be considered for existing and planned reservoirs. For all large natural lakes in Switzerland, evidences of large historical tsunamis have been documented with many of them also causing casualties (e.g. 1584 in Lake Geneva, 1601 in Lake Lucerne, 1687 in Lake Lucerne, 1806 in Lake Lauerz).

Past research mainly focused on subaerial slide induced impulse waves, i.e. the slide is initially located above the still water surface. The slide then accelerates, impacts the water surface and transfers its momentum to the water, thereby creating an impulse wave. The wave generation process was intensively studied in the 11.0 m long, 0.5 m wide and 1.0 m deep impulse wave channel at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). Using a unique pneumatic landslide generator, the governing initial parameters (slide impact velocity V_s, slide volume $\forall_s$, slide density ρ_s, slide thickness s, slide length L_s, slide granulometry d_g, slide impact angle α, and still water depth h) were varied independently in more than 400 tests conducted within 3 PhD theses. In 2009, an assessment guideline on "Landslide generated impulse waves in reservoirs" was published by VAW, summarizing past VAW research and a literature review.

In contrast to subaerial slides, only few experimental investigations on submarine slides are reported in literature. Field observations are difficult since the slide events and their locations often remain unnoticed. Whereas subaerial mass movements are triggered only on rather steep slopes, underwater slope failures may occur for relatively small angles ($\alpha \leq 20°$), since buoyancy and water pore pressure reduce the slope stability. Even weak earthquakes can then trigger slope failures. Submarine slides accelerate underwater until a terminal velocity is reached. The driving force created by the gravity acceleration is then in equilibrium with the retaining force, created by the slide drag. The slide drag is a function of the slide shape, the slide velocity and the turbulence characteristics. Depending on the lake bathymetry and the initial slide submergence, the underwater travel distance may be too short to reach this kinematic equilibrium. Whereas for the previously investigated subaerial slides the slide velocity was a relevant input parameter, the slide velocity of submarine slides is not known in advance but is a result of the combination of initial parameters.

Together with the University of Berne, the Swiss Seismological Service, and the Center for Marine Environmental Services, Bremen (D), VAW is involved in a current SNF-Sinergia research project, aiming at an overall description of triggers for slope failure, wave mechanisms and a probabilistic lake tsunami hazard assessment. Physical model tests are therefore conducted in the above mentioned impulse wave channel equipped with a new slide release mechanism. A metal sheet protruding 10 cm into the water retains granular slides with a volume of $\text{Ꝟ}_s \approx 0.01$ m^3. The metal sheet fully retracts within ≈0.08 s thereby releasing the granular slide. The granular material with grain diameters d_g = 2 … 8 mm consists of 87% Barium Sulfate compounded with 13% Polypropylene resulting in a grain density of ρ_g = 2.55 … 2.69 kg m^{-3}. The submarine slide motion is recorded by a pco.edge sCMOS high speed camera with an acquisition rate of 50 frames per

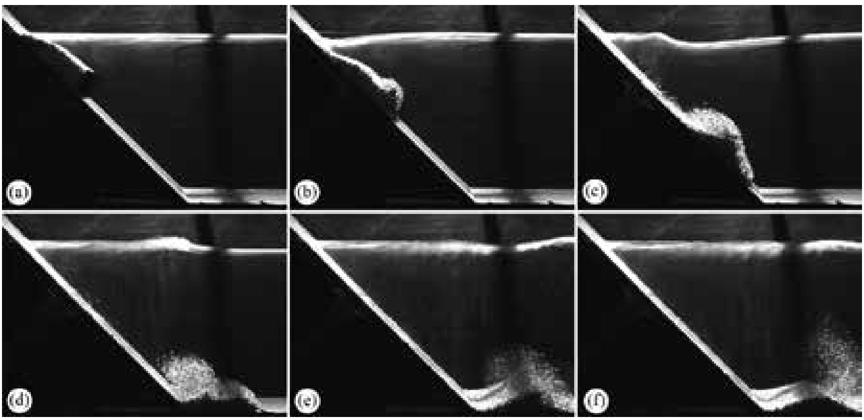

Figure 1: Image series of impulse waves generated by a granular submarine landslide in laboratory (slide angle α = 45°, still water depth h = 0.7 m, slide volume $\text{Ꝟ}_s \approx 0.01$ m^3, grain diameter d_g = 8 mm, initial slide submergence d ≈ 11 cm, maximum wave height $H_M \approx 54$ mm), time increment between images is Δt = 0.5 s.

second. The slide contour at the glass side wall is extracted manually from still images using the software WebPlotDigitizer. Based on the slide contour, further slide characteristics, e.g. the slide centroid location, slide length and slide velocity are determined. In addition, the free water surface is tracked to determine the resulting wave characteristics (amplitude of wave crest and trough, wave length) in the generation zone. For streamwise channel locations $x \geqslant 0.8$ m from the initial shoreline, the water surface deformation is recorded pointwise using six Ultrasonic Distance Sensors.

An image series of impulse waves generated by a granular submarine landslide is shown in Fig. 1 for a slide angle $\alpha = 45°$, still water depth $h = 0.7$ m, slide volume $\forall_s \approx 0.01$ m^3, grain diameter $d_g = 8$ mm and initial slide submergence $d \approx 11$ cm. Figure 1(a) corresponds to the initial condition at $t = 0$, directly prior to slide release with both the slide and water totally at rest. The slide accelerates down the slide plane in Fig. 1(b). The slide front disintegrates because additional water enters the pores. A wave trough is formed directly above the moving slide, as the free water surface follows the downward oriented slide motion. The slide further accelerates on the slide plane in Fig. 1(c) with a maximum velocity of $V_s \approx 1.0$ m s^{-1}. The slide cross section is triangular with a distinctly disintegrated surface caused by turbulence. The wave through is still visible and an additional wave crest has formed above the slide plane resulting in a wave height of $H(t = 1.0 \text{ s}) \approx 44$ mm. The wave crest is very steep and tends to break. The slide reaches the horizontal bottom in Fig. 1(d). A large 'cloud' of granulate material follows the slide at its trailing edge indicating turbulence. The breaking wave crest is located directly above the slide. Whereas the slide material is almost at rest in Fig. 1(e), the granulate 'cloud' further propagates into the water body and the breaking wave crest leaves the field of view. The slide deposits are at rest in Fig. 1(f), however, the granulate 'cloud' now located at the slides leading edge is still pronounced, again pointing at large vortex formation and the corresponding turbulence. Only minor secondary waves are visible at the free surface.
Based on the first 41 tests and involving the relative slide mass $M = (\rho_s \forall_s)(\rho_w b h^2)^{-1}$, the relative maximum wave height can be estimated by

$$\frac{H_M}{h} = \frac{1}{5}\left(\frac{d}{h}\right)^{-\frac{2}{5}} M^{\frac{3}{5}} (\sin\alpha). \qquad (R^2 = 0.88)$$

In addition to the improved general process understanding, the data obtained apply for hazard assessment and to calibrate a calculation procedure or to validate numerical models. This work thus contributes to the estimation of the risk assessment and to safety aspects relating to wave-shore interaction mainly in the Alpine environment.

Observation guided constitutive modelling for creeping landslides

Philipp W. Oberender [1], Alexander M. Puzrin [1]

[1] Institute for Geotechnical Engineering (IGT), ETH Zurich

Landslides that show very slow "creeping" movement are a common phenomenon in many mountainous areas. Though human fatalities are rarely caused by creeping landslides, continuing urbanization of landslide prone areas results in severe damage to buildings, roads and other infrastructure. Another potential hazard of such landslides is their catastrophic acceleration. Therefore investigating mechanisms of such landslides is essential for providing guidance for decision makers regarding safe construction and future urban development in such areas.

Understanding of landslide mechanisms is often aided by numerical models targeting three major areas:

(i) Relation between precipitation/snow melt and pore pressures in the landslide – **hydrological model**

(ii) Material behaviour along the slip surface, i.e. the interface between stable and unstable ground – **constitutive model for the slip surface**

(iii) Material behaviour inside the landslide body – **constitutive model for the sliding body**

Determination of the three suitable models is often difficult due to a lack of data regarding landslide geometry, complex hydrology, a presence of discontinuities and soil heterogeneity. Therefore, "top-down" approaches where the models are calibrated based on laboratory data and then applied to a landslide model often face difficulties to reproduce field observations of the actual landslide behaviour. Oberender and Puzrin (2016) proposed a different "bottom-up" approach to constitutive modelling for creeping landslides, based on the observed landslide behaviour - observation guided constitutive modelling (OGCM).

OGCM treats the landslide as a series of full scale shear and compression elements and aims to derive not only parameters but also suitable constitutive models directly from observations of the landslide displacement rates. Loading of these elements is defined by earth and water pressure derived from field observations and solutions of simple transient 1D boundary value problems.

To ease the process of model calibration, generalized hydrological and constitutive models are proposed, which are capable of reproducing a number of phenomena observed in creeping landslides. Within the OGCM-process these generalized models can be reduced to the features needed to capture observations at one specific landslide site. Since the number of unknowns at most creeping landslide sites is high and in order to reduce complexity of the models, simple formulations for all three sub-models have been adopted.

The hydrological model is based upon linear reservoirs relating effective precipitation to pore pressure fluctuations. The constitutive models for slip surface and sliding body are based upon fundamental visco-elastic-plastic elements that allow phenomenological representation of

- strain softening, rate dependency and, if necessary, elastic pre-failure deformations along the slip surface and
- elastic deformations, delayed creep and relaxation, as well as development of failure or yielding in the sliding body.

The constitutive models are integrated into a boundary value formulation described by a conceptual 1D model of the landslide. Numerical simulations of the boundary value problem allow calibrating the models and adjusting the necessary level of complexity.

Application of the OGCM process is demonstrated using the case of the Brattas landslide in St. Moritz. This approximately 700 m long landslide of is constrained at the bottom by a rock outcrop that stops the landslide in the canter of the town of St. Moritz.

Long-term displacement records in combination with precipitation records, laboratory investigations and field tests allowed deriving suitable models for different regions along the landslide using OGCM.

Large displacement rates and rate fluctuations in the upper part of the landslide (region I) and a significant drop in rates and temporal fluctuations in the overbuilt part (region II) have been captured (see inset in figure 1).

Additionally the very complex behaviour close to the boundary (region III) where the landslide de-and reaccelerated over time (figure 1) under transient loading due to precipitation could be modelled successfully.

Successful application of the adaptable OCGM approach to the complex Brattas landslide validated its ability to derive creeping landslide models relying mainly on observational data. The proposed models can evolve in space and time not only allowing understanding past observations but also modelling future development scenarios. The hierarchical nature of the approach and simplicity of the sub models eases the process of model derivation and understanding of the landslide behaviour.

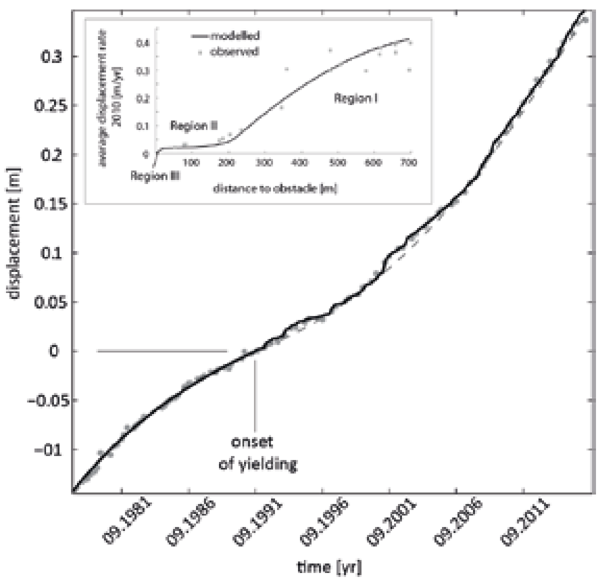

Figure 1: Development of displacements close to the boundary (region III); Inset: Velocity profile along the landslide

References:

Oberender, P. W., & Puzrin, A. M. (2016). Observation-guided constitutive modelling for creeping landslides. Geotechnique, 66(3), 232–247. Journal Article. https://doi.org/doi:10.1680/jgeot.15.LM.003

Earthquake (and natural hazard) resilience of communities

Božidar Stojadinović [1], Max Didier [1], Li Sun [1], Marco Broccardo [1,2], Panagiotis Galanis [3], Simona Esposito [4]

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After sustainability, resilience is the most sought after quality of a community. A resilient community is one that bounce back after a severe disruption. As civil engineers, we focus on natural disasters and the built environment that supports the social and economic functions of a community. Our goal is to define, model and design resilient communities, i.e. engineer the community built environment for natural disaster resilience.

The functionality-based definition of community resilience, pioneered by Bruneau, has taken root. Based on this definition, we developed a compositional supply/demand resilience (ReCoDeS) framework suitable for modeling and quantifying the resilience of civil infrastructure systems that supply services consumed by the community inhabitants. We verified the framework on several studies of seismic and tornado resilience of virtual communities and validated it using the data on the vulnerability and recovery of the electric power, water and cellphone communication systems in Kathmandu, Nepal after the 2015 Gorkha earthquake. The instantaneous and cumulative measures of resilience, established within the ReCoDeS framework, make it possible to define engineering acceptance criteria and to evaluate the natural hazard resilience of a community.

Engineering a resilient community is complex. In addition to understanding the hazards and mastering the engineering aspects of the vulnerability and recovery of the community built environment, making a community more resilient involves economic and social considerations that are often outside of the domain of structural engineering. Therefore, the ReCoDeS framework is, also, a platform for multi-disciplinary collaboration. We already used agent based and network theory models to simulate the recovery process. More complex models, involving optimal construction resource allocation and improved cost and duration estimates, are needed to enable urban development and financial resource allocation, all with the goal to prepare communities to tackle natural disasters and build a more resilient society.

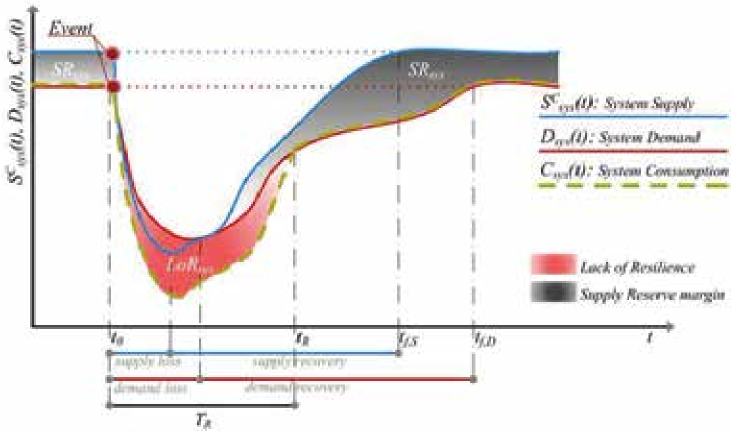

Figure 1: Development of displacements close to the boundary (region III); Inset: Velocity profile along the landslide

Uncertainties in seismic hazard and risk analyses: the good, the bad and the way ahead

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The ultimate goal of earthquake engineering is to ensure life safety and to minimize built environment losses by reducing seismic risks to economically acceptable levels. In this study, we chronologically review the basic principles used to characterize the seismic risk. We finally outline the limitation of the methodology, which can be improved using a more holistic approach that embraces the most recent advancement in the field of uncertainty quantification and stochastic dynamics.

In 1968, Allin Cornell set the foundations for the Probabilistic Seismic Hazard Analysis (PSHA) in his noteworthy study "Engineering seismic risk analysis". At present, the article counts more than 3360 citations and continues to represents the backbone of the method. In essence, PSHA provides a comprehensive framework to describe the seismic hazard in a given location. The nature of the framework is inevitably probabilistic since the uncertainties related to location, size, and ground motions are proven to be large. The output of PSHA analysis is generally the exceedance rate of one or more given ground motion intensity measures (IM), for a given location and time interval. PSHA analyses have a broad spectrum of application; an incomplete list includes the definition of regional hazard maps, the definition of the baseline for seismic design codes, and the determination of earthquake insurance policies. In its simplest and original form, PSHA is based upon four fundamentals (Figure 1a):

(i) Identification of the seismic sources (e.g. faults locations and geometry) and probabilistic characterization of the site-to-source distance.

(ii) Definition of the time occurrence model of the seismic event (typically a Poisson process) and earthquake magnitude distribution (typically a truncated exponential distribution).

(iii) Selection of an IM (e.g. peak ground motion and spectral acceleration) and definition of a probabilistic model to link IM, magnitude, and the source to site distance. Typically, the probabilistic model is a regression model and the derived relationships are referred to as Ground Motion Predictive Equations (GMPEs).

(iv) Given the joint probability distribution of IM, magnitude and site-source location, the rate of exceedance of IM is given by the application of the total probability theorem.

A crucial aspect of the method is the definition of the GMPEs. Briefly, the GMPEs are based upon seismic catalogs, which, in their simplest form, consist of seismic events grouped by fault mechanism, magnitude, source-to-site distance and soil condition. Based on the catalog, the intensity measures are extracted from the seismic waveforms recorded at different locations and regressed against magnitude and distance (and eventually other variables). Observe that the reduction of a waveform to a single (or few) IM(s) comes at the price of dropping physical information encoded in the full record.

The rates of exceedance curves, which are the output of seismic hazard analysis, become the input for seismic risk analysis. In 2000, a short note—"Progress and challenges in seismic performance assessment" written by Cornell and Krawinkler for the Pacific Earthquake Engineering Center (PEER) —established the foundation of what is now known as the PEER-PBEE framework (where PBEE stands for Performance Based Earthquake Engineering). Following the PSHA structure, the PEER-PBEE framework aims at computing the mean annual rate of a performance measure exceeding a given threshold. The framework builds on four major stages (Figure 1 b):

(i) *Hazard analysis*: the output of PSHA analysis, i.e., the rate of exceedance of a selected IM.

(ii) *Structural/fragility analysis*: the analysis evaluates the probabilistic relationship between the selected IM and an engineering demand parameter (EDP), which represents the structural performance (e.g. maximum displacement of a critical structural component).

(iii) *Damage analysis*: evaluates the relationship between EDP and a damage measure (DM). The relationship can be deterministic or probabilistic. In the first case, this analysis can be blended with fragility analysis.

(iv) *Loss analysis*: evaluates the probabilistic relationship between a given decision variable (DV) and a given damage measure DM. The decision variable measures the seismic performance of the facility in terms of stakeholder interest (e.g. monetary loss).

The main advantage of the framework is that it builds on four distinct stages, which are handled by different groups of experts. This decomposition is made possible through the Markov assumption that conditional on stage ii., stage iii. is independent from stage i., and, conditional on stage iii., stage iv. is independent from stage ii. and i. While this assumption clearly has the merit of simplifying and decomposing the problem into conditional independent tasks, it has also few drawbacks. A key component of the framework, stage ii., has attracted a vast amount of attention. Specifically, most of the efforts were concentrated on developing a robust methodology, which utilizes the know-how of well-established disciplines such as non-linear structural analysis to consistently compute the EDPs. The major problem is that the response of a structural system to earthquake excitation is a complex phenomenon that is difficult to model if the input is reduced to only one or few IMs. Non-linear structural analysis, on the other hand, provides a suitable setting to perform such analysis, given that the input is a seismic waveform. Since the output of PSHA analysis is either one or a limited number of IMs, different techniques were developed to select seismic waveforms, conditioned on the IM. Moreover, since data for large Magnitudes and a given location is scarce, questionable practices, such as scaling existing records, have been widely used. The core issue is that different disciplines, which have historically developed independently, are fit in a simple but "strict" framework. Moreover, the conditional independence structure might not adequately represent the correlation structure among the variables of the problem. Therefore, we propose to relax the Markov condition and promote the use of tools such as copula models, multivariate extreme value theory, and stochastic dynamics to adequately study and quantify the dependence among the variable of interests, from the source to the final decision variable.

Within the cross-disciplinary spirit of the D-BAUG workshop, this talk calls for a more holistic approach for seismic risk analysis; one that embraces a deeper (rather than independent) collaboration among the seismologic community, the earthquake engineering community and the uncertainty quantification community.

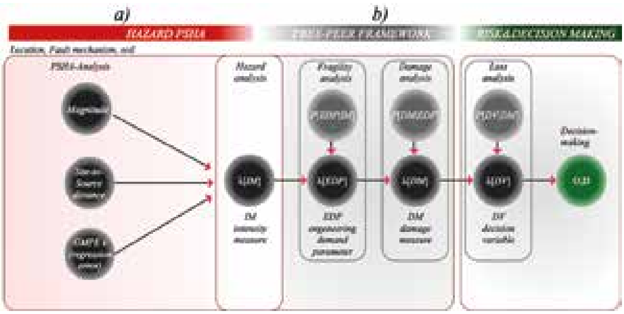

Figure 1: Simplified PSHA and PBEE-PEER framework for seismic risk evaluation

Contributions of GNSS to earthquake hazard monitoring and assessment

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In the last two decades the Global Navigation Satellite Systems (GNSS), comprising the US American GPS, the Russian GLONASS, the European Galileo, the Chinese Beidou and the more regional Japanese QZSS and Indian INRSS, have become a very important tool not only for navigation and positioning, but also for the monitoring of the diverse processes in the Earth's system. These processes may happen in time scales from very long (melting of ice sheets, sea level change, plate tectonics, ...) to extremely short (earthquakes, volcano eruptions, landslides, ...). Appropriate monitoring and early warning systems must allow, therefore, the detection and quantification of catastrophic events in (near) real-time on the one hand and the reliable identification of barely noticeable, but crucial long-term trends (e.g., sea level rise) on the other hand. GNSS enables the exact measurement of both, deformations over decades and displacements in real-time, providing valuable clues to plate tectonics, geodynamics, earthquake processes, tsunamis, volcanos, landslides, glaciers dynamics and more.

In this presentation, we focus on our GNSS contributions to displacements from long-term plate tectonics to near real-time earthquake monitoring. Making use of large permanent GNSS networks operated nowadays, we can draw the bow from geodynamics on global, regional and local scale, the detection of transients (silent earthquakes; e.g. in Cascadia) to the observation of the ground motions during earthquakes. With GNSS receivers that measure with sampling rates of up to 100 Hz, it is possible to capture the earthquake waveforms like a seismometer, a technique called GNSS seismology. We illustrate this technique based on the GPS data of the Tohoku-Oki earthquake, taking place in Japan on March 11, 2011 (see Figure 1) and we assess its accuracy using well-defined shake table experiments.

In view of the fact that, in a few years, more than 120 GNSS satellites will be available and tens of thousands of permanent GNSS stations will be collecting data, a revolution is taking place in space geodesy.

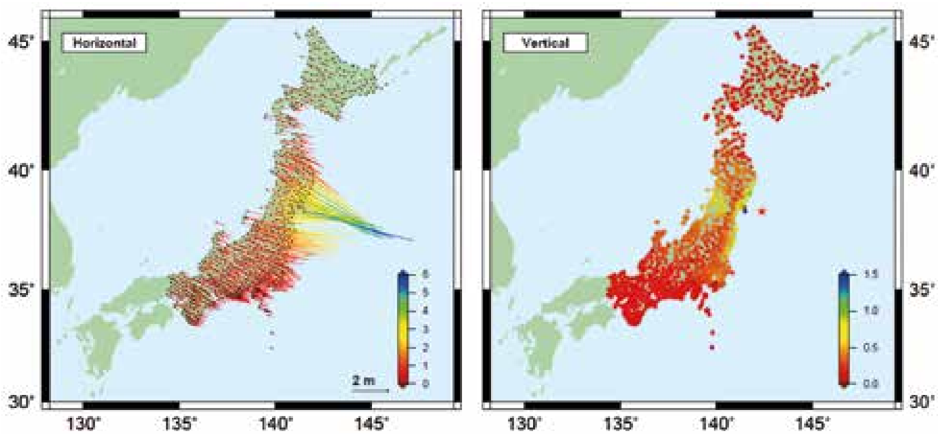

Figure 1: GPS-derived maximum horizontal (left) and vertical (right) displacements (in m) for the Tohoku-Oki earthquake in Japan on March 11, 2011.

Determination of tectonic and landslide strain patterns from geodetic deformation observation and analysis

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Geodetic measurements for strain determination are in many cases carried out at the Earth's surface, thus topologically they remain in a 2D manifold. Even though changes in the third component are determined e.g. by levelling it will hardly be possible to determine the real 3D strain. Our method circumvents this problem by introducing a crustal model. Even simple models help and deliver quite realistic results as shown in this presentation. In the case of Switzerland, however, this remains very demanding because of the very small yearly movements generating equivalently small yearly crustal distortions at a maximum of 25 nstrain per year.

The available time series of GNSS and levelling measurements acquired and treated by the Swiss office of topography, are sufficiently long to reveal deformations in Switzerland. They make it possible to determine a coherent kinematic deformation field of Switzerland by geodetic means.

Further development of the ‚Adaptive Least-Square Collocation (ALSC)', which was devised at ETH, and the implementation of a physical crustal model made it possible to directly calculate a three dimensional strain tensor field out of the available measurements e.g. GPS and levelling. The geodetically determined strain-tensors are verified versus focal mechanisms obtained from seismological data. The mechanism of a recently induced earthquake mechanism in the region of St. Gallen close to a geothermal test site is in agreement with the strain tensors determined by GPS-data. The described method can also be applied to more local events, e.g. the analysis of subsidence or landslides. It will allow gaining more insight into subsurface processes by geodetic measurements. The measurements may also encompass optical or radar methods. An example of slow moving landslide application will be shown together with a new GNSS movement detector as well as results of geodetic determination of strain field in the complex tectonic setting of the Swiss Alps.

Presented projects are partly funded by the Swiss Nat. Sci. Foundation (Nano-Tera Programme), the Competence Center Environment and Sustainability of ETH Domain (CCES), FOEN and swisstopo.

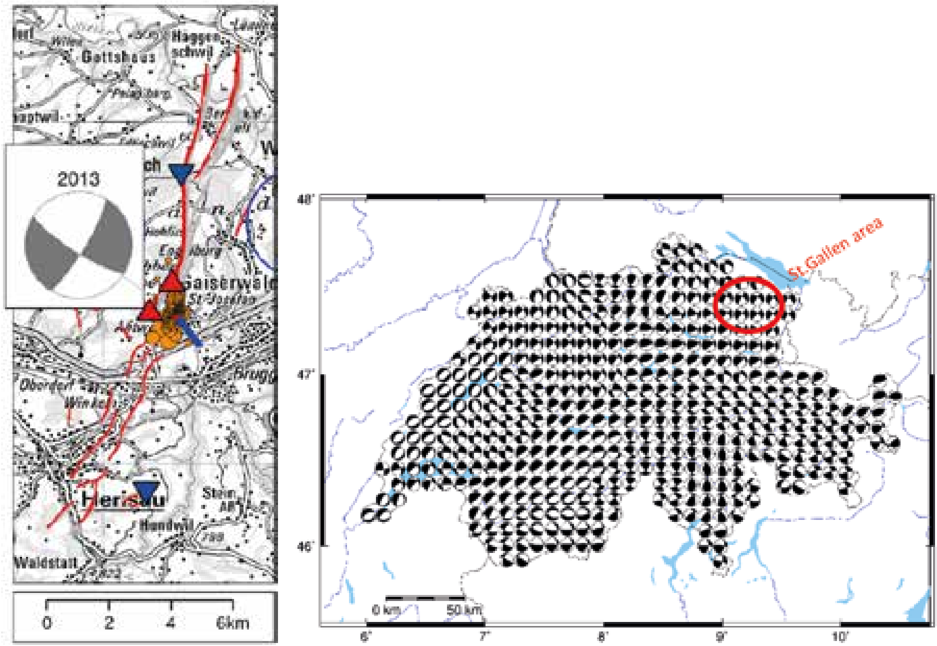

Figure 1: Earthquake fault solutions derived by GNSS only (right). Earthquake triggered in St. Gallen (SED,2013) (left). It corresponds well to the anticipated solutions (above).

Study of the seasonal response of a steep scree slope in the Swiss Alps

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The Meretschibach catchment includes a steep (33° - 43°) alpine slope between elevations of 1500 to 2000 m.a.s.l, above Agarn village at 620 m.a.s.l, in canton Wallis, Switzerland. The alpine catchment is composed of several parts, with two investigated in this project including a steeper section, which has been eroded to bedrock and is called the dry channel, and an adjacent scree slope. Debris are produced by failure, disaggregation or toppling from exposed bedrock faces in the upper part of the mountain slope, whereupon they are deposited either in the channel or on the steep slope. Remobilisation of the deposited debris can be triggered by meteorological events such as rain and thawing of snow, ice and frost, leading to erosion and initiation of a debris flow in the dry channel or surficial slides on the slope.

The study originally consisted of two projects and was submitted to the SNF for funding. Additional subsidiary funding was obtained from the Agarn and Leuk Councils. Project 1 aimed to determine the temporal behaviour and spatial distribution of slope instabilities at Meretschibach, combining the use of ground based portable radar interferometer and a characterisation of the source area. This provides the input for frequency-magnitude relations of the mass movement and runout modelling of the hazard scenarios in the dry channel. Project 2 focused on characterisation of the adjacent scree slope (e.g. slope inclination, geology, bedrock depth, soil layering and properties), monitoring of saturation and desaturation in the slope and other meteorological data (precipitation intensity in the form of rain or snow, snow depth) and a study of the mechanisms of failure triggered by rainfall and other saturation processes (snow melt, water flow) through numerical and physical modelling.

Although project 1 would have contributed to estimating the debris flow hazard to Agarn village, only project 2 was funded by the SNF, so a reduced programme was pursued to understand the dynamics in the catchment and the processes of production and remobilisation of sediments and debris and triggering mechanisms of debris flow in the dry channel. Given that the debris flow hazard could cause loss of life and damage, depending on the flow volume and velocity, providing basic tools for the prediction of the hazard and development and improvement of an early warning system was also accomplished through the fourth author and cooperation with the WSL.

The remainder of this abstract focusses on geotechnical doctoral project 2, conducted by the first author, and a geophysical master's project by the second author. The initial hypothesis was that surface erosion or creep (measured by remote sensing conducted by the third author) could be coupled with meteorological and hydrological processes and that this might lead to a mechanism of failure in the slope. When rainfall occurs, water infiltrates into the scree slope, producing a loss of suction in the finer grained deposits before increasing the pore water pressure, with a subsequent reduction of effective strength and an increase in the potential for landslide hazards. Although ravelling subsequently proved to be a more critical mode of erosion, characterisation and monitoring over a period of 3 years to investigate the prior hypothesis provided an extremely valuable dataset.

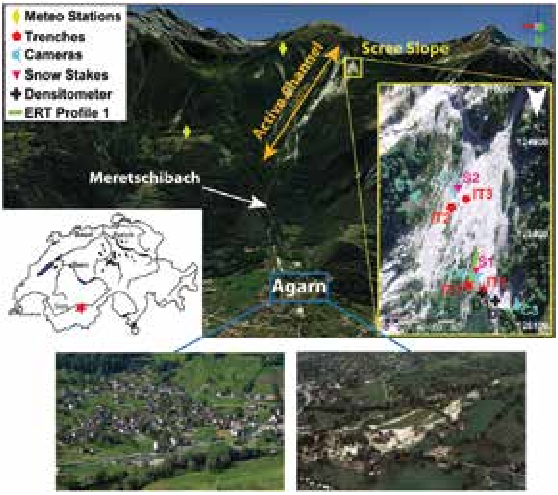

Figure 1: Overview of the field area, located in canton Valais, Switzerland (star on small map). The image looking south shows a view of Agarn, situated on the Rhone valley floor and the Meretschibach catchment on the mountain slopes behind. The most active area within the catchment can be divided into an active channel and a scree slope. The weather stations (yellow diamonds) are located at 1370 m.a.s.l. (IGT) and 2220 m.a.s.l. (WSL). The right image shows an enlargement of the scree slope (yellow rectangle) with the locations of the instrumented trenches (IT1-IT4), the ERT profile on which the monitoring was performed, snow stakes (S1–S2), densitometer measurements (D1–D4) and cameras (C1–C4), At the bottom left the Village of Agarn and to the right the debris deposited in Briannen (Agarn) on the15th of October 2000 (Source: Google Maps and Markus Zimmerman).

Characterisation of the scree slope relied on complementary geophysical measurements, including Electrical Resistivity Tomography (ERT), to determine that a highly resistive layer attributed to the bedrock was found between 1-3 metres in depth. Test pits were dug at four locations to expose the soil layers, and to establish whether there was any consistent ground model above bedrock. Insitu tests were carried out to obtain insitu densities. Soil samples were extracted for subsequent laboratory testing, including large scale constant shear drained triaxial stress path tests, representing saturation on reconstituted 15 cm and 25 cm diameter specimens, obtaining a friction angle of 41°.

Long-term geotechnical monitoring included insitu soil temperature, suction and volumetric water content measurements using dielectric permittivity and time domain reflectometry (TDR). The sensors were installed in four instrumented trenches IT1-4 in the scree slope. A 2D ERT survey was carried out next to instrumented trench IT1 to determine soil moisture and complement the point measurements from the TDRs and dielectric permittivity sensors, yielding reasonable agreement. The datasets are completed by recordings from two nearby weather stations. Seasonal changes of precipitation and temperature were reflected in corresponding trends in all soil measurements at the scree slope. The characterisation and monitoring results provided input for a ground model, which integrates all available parameters, and delivers essential information and boundary conditions for predicting and validating slope instabilities. This ground model plus rain data is used in the numerical and physical modelling to simulate different scenarios of rain intensity infiltration, soil thicknesses, as well as cases of pre-existing ground water conditions. This stage of the project in still in progress.

The most critical failure mechanism had been expected to be due to shallow landslides, triggered by rainfall infiltration and lateral flow in a saturating soil that is heterogeneous in terms of porosity and grading. Given that the slope angle was between 33° and 43° and the friction angle is 41°, there is potential for small slips to occur if pore water pressures become positive over a significant depth or springs form on the slope. However, it was observed during the monitoring campaign that the ground did not saturate over a large enough volume and the greatest number of downslope movements arose either from boulders falling and toppling downslope, being deposited temporarily, and remobilised either by repeated cycles of freezing and thawing, and snow-melting processes in winter or eroded by rainfall and runoff during the rest of the year. Nonetheless, numerical and physical modelling will allow different scenarios for rain intensity, bedrock geometry and soil thickness to be tested.

3D DEM study of stick-slip in granular fault gouge; effect of vibration and fluid saturation

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The aim of our numerical studies is to understand the frictional behavior of granular materials with application to stick-slip dynamics in fault gouge. Fault gouge is a granular layer created by fragmentation and wear of rock. The stick-slip dynamics in fault gouge is believed to drive earthquake cycles in earth. Elastic energy is stored during the stick phase and released suddenly during slip. The granular assembly in our discrete element studies is composed of spherical particles confined vertically and sheared horizontally. We did a phase-space study to find the normal load and shear velocity that promote stick-slip. Slip events are associated with a sudden release of particle kinetic energy indicating strong particle rearrangements (as shown in Fig. 1a). These particle arrangements lead to macroscopic observations like a drop in friction coefficient and compaction of granular layer.

We study the effect of fluids on the characteristics of slip events i.e. friction coefficient drop, kinetic energy release and layer compaction. For the saturated case, a discrete element model (DEM) is coupled with a computational fluid dynamics (CFD) model to model the two-phase system. We use an unresolved CFD-DEM approach in which each CFD grid contains several particles. For the partially saturated case, we use a DEM model enriched with a capillary bridge model to include cohesive/viscous forces. We perform long time trains of slip events in dry and saturated systems and collect information of hundreds of slip events. The statistical observations show that in fully saturated system, the slip events experience longer recurrence time, equivalent to storage of more energy leading to larger slip events. Our grain scale observations show that presence of fluids can make the granular layer more stable evidenced by higher coordination number, leading to longer stick phases [Dorostkar et al., 2017b]. We also show that during slip, fast fluid flow (Fig. 1d) occurs due to drag from particles on fluid (Fig. 1c), and in turn drag force from fluid on particles leads to further mobilization of the granular layer [Dorostkar et al., 2017a]. In the partially saturated case, the cohesive/viscous forces between wet particles tend to stabilize the granular medium

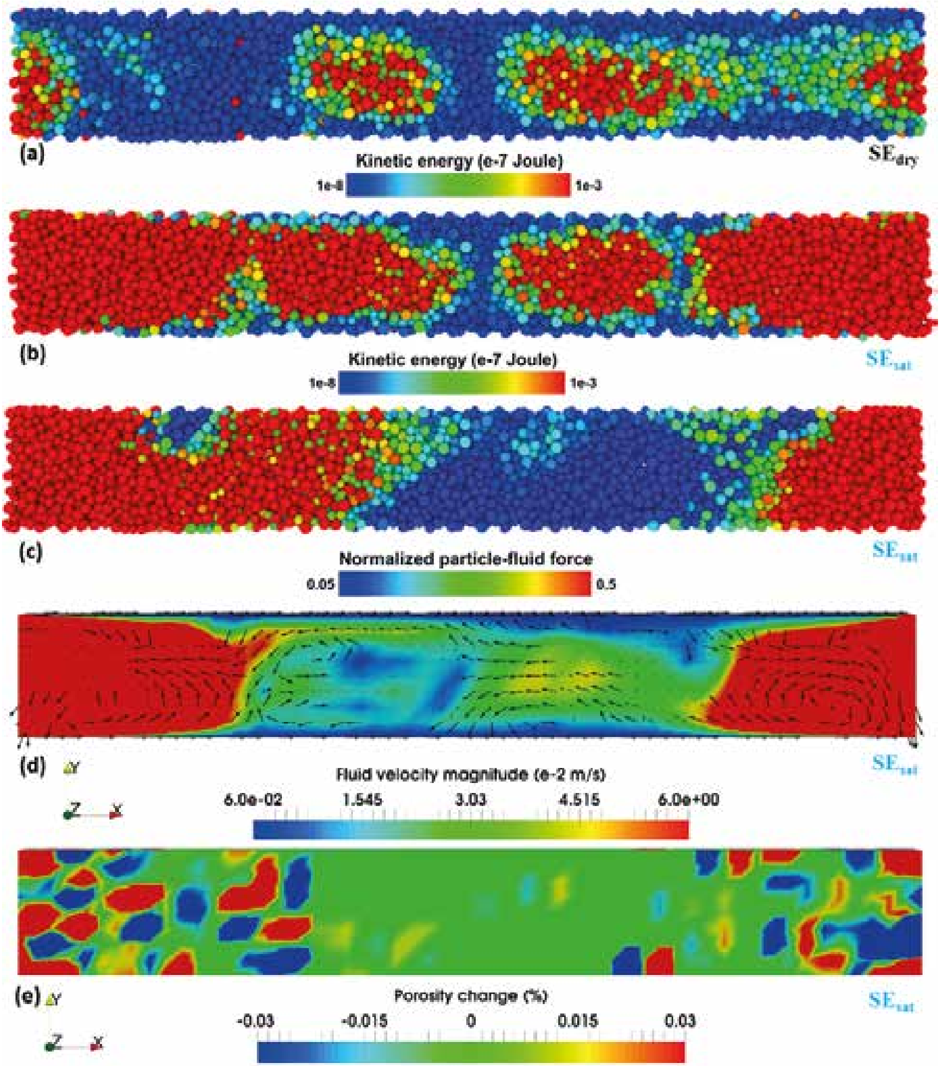

Figure 1: (a-b) Distribution of kinetic energy of particles for a major slip event: (a) dry case and (b) fluid saturated case. (c) Normalized particle-fluid interaction forces from fluid on particles. The value of particle-fluid interaction forces is normalized by the average value calculated for all particles. (d) Fluid velocity field and (e) porosity change in fluid saturated model.

during stick phase increasing the friction coefficient and thickness, but also increasing the size of the slip event.

We also study the effect of vibration to simulate dynamic earthquake triggering in a dry fault gouge. Results show that when vibration is applied in the stick-phase above a threshold amplitude, a clock advance of a major slip event occurs [Ferdowsi, 2014; Ferdowsi et al., 2014a; Ferdowsi et al., 2014b]. In short term after vibration, a suppression of energy release in the perturbed simulations is observed, or less slips occur. In long term after vibration, more energy release and higher slip activity in the perturbed run is observed that compensates for the temporary suppression of energy release just after vibration. We observe that by increasing the vibration duration, the friction drop during the frictional weakening events increases for similar vibration amplitudes and that the minimum vibration amplitude required for inducing a clock advance gradually decreases [Ferdowsi et al., 2014a].

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Challenges in assessing road related risk to plan risk-reducing interventions

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The goal of road network management is to obtain the maximum net-benefit from the road infrastructure, taking into consideration how all stakeholders are affected, economically, environmentally, and socially. In planning interventions on the infrastructure to maximize the net-benefit, road managers need to estimate what might happen to it in the future, as well as the consequences and probabilities of occurrence of these futures, i.e. risk.

The estimation of road related risk is challenging because, 1) it requires the modelling of a complex system, and 2) this system has an infinite number of ways that it might evolve in the future. To deal with these challenges, it is necessary to involve, 1) analysts with different expertise, e.g. in climate modelling, in hydrology, in geology, in structural analysis, in traffic modelling, and in the planning of interventions, (illustrated in Figure 1) and 2) stakeholders with different perspectives on the value of the consequences related to the possible futures, e.g. the costs of restorative interventions, the costs of service interruptions and the costs of changes to the system in which the infrastructure is embedded.

This presentation includes an overview of these challenges, and a proposal, in terms of steps and possible collaborations, to overcome them. The presentation will draw on the experience gained in a recent assessment of the risk related to the road network in the region of Chur, Switzerland due to rains that could lead to flooding and landslides.

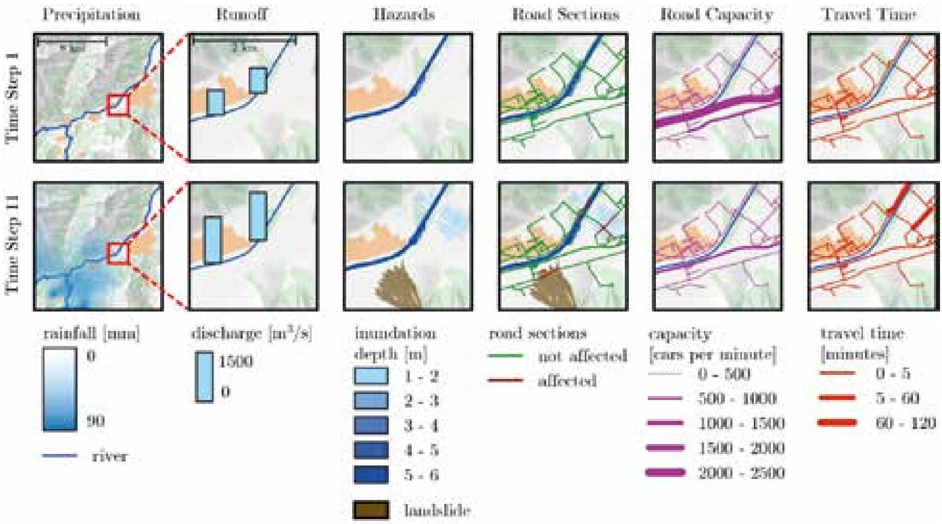

Figure 1: Views of multiple aspects of the system model used to assess network related risk

The potential of new data sources to improve urban flood modelling

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Urban pluvial flooding

Pluvial flooding in urban areas is a complex phenomenon involving coupled surface and sewer flow, and having the potential to cause important damage to lives and property. Urban drainage planners, who design drainage and infiltration infrastructure to mitigate urban flooding and sewer overflow, are often forced to make expensive, strategic decisions based on approximate hydraulic models calibrated only with sewer flow data from a limited number of events. The lack of surface flow measurements is translated into an information deficit that introduces large uncertainties into the model and its forecasts, complicating the task of urban drainage planners and managers.

New data sources and computer vision methods

While remote sensing can currently provide discretionary detail for some of the required modelling data such as elevation data, it is limited when it comes to surface water measurement. The wealth of image and video material on social media networks has the potential to provide these otherwise hard to obtain measurements (e.g., flood levels and flow velocities) thanks to automatic computer vision tools. With an appropriate weighting system, these additional and sometimes uncertain measurements can be used to calibrate urban flood models in a systematic way.

Currently, we are investigating the application of existing image processing methods and developing new ones to extract flood measurements from image data in urban environments. On one hand, this consists in the video-based speed estimation of untraced shallow urban surface flows. The idea is to extend Large-Scale Particle Image Velocimetry (LSPIV) to urban surface flow conditions. On the other hand, we will apply deep learning to perform automatic semantic image interpretation for (i) screening images for large bodies of water and (ii) estimating water levels by identifying standard-sized objects in the image scene.

Urban flood experiments

In order to investigate the advantages of the newly available data sources, we have conducted a series of flood experiments (Moy de Vitry et al., in review) in a flood facility that is typically used for rescue training which allows controlled flooding of a 25x25 m area that contains a building and a simple configurable sewer network. The flood water storage tank holds 450 m^3 of water which and can be released at a maximum rate of around 500 $l\ s^{-1}$; it refills automatically every 24 hours. This unique facility has the advantage of being able to reproduce all relevant urban drainage processes (sewer drainage, surface flow and sewer surcharge), except infiltration.

First preliminary results: estimating surface flow velocity in urban areas

The first investigations have focused on testing the application of LSPIV to shallow surface flow in urban areas. The images used to conduct the tests were acquired during the flood experiments campaign mentioned above, using conventional surveillance cameras (CCTV). The LSPIV flow estimations were compared to the measurements obtained using conventional radar-based flow sensors also available during the flood experiments campaign, and the obtained values were similar: 0.92 $m\ s^{-1}$ (Fig. 1) and 0.90 $m\ s^{-1}$ for a particular time step, respectively.

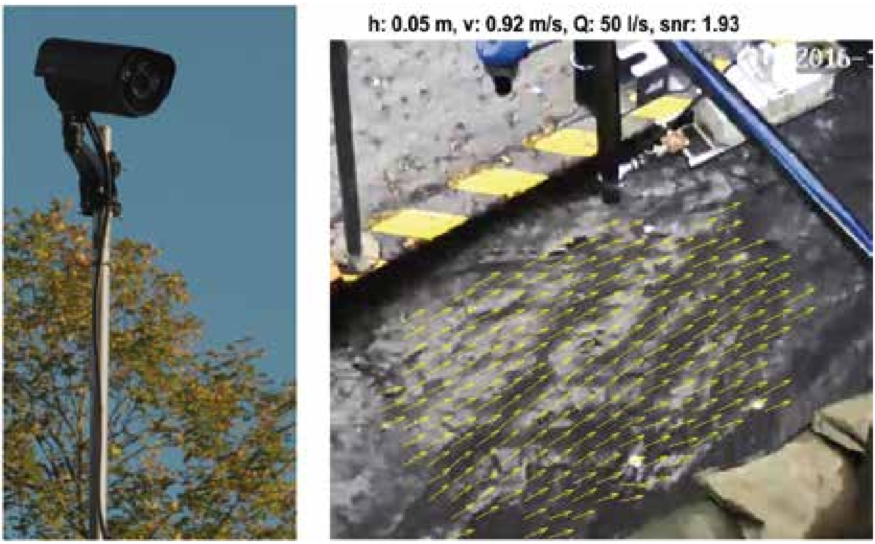

Figure 1: Estimating surface flow velocity based on CCTV footage and Large-Scale Particle Image Velocimetry (LSPIV). Left: CCTV camera used; Right: LSPIV flow estimation results.

On-going and future investigations

Regarding the applications of LSPIV to estimate flow velocities of urban runoff, further tests and comparisons are being conducted to investigate the factors that affect measurement accuracy.

In parallel, the application of deep learning is being investigated in order to extract further information out of CCTV data. The objective is to perform semantic segmentation to monitor the changes of water-covered surfaces over time. The time series thus obtained can be used to calibrate and validate urban flood simulations.

References:

Moy de Vitry, M., Dicht, S., Leitão, J.P. (in review). floodX: Urban flash flood experiments monitored with conventional and alternative sensors. Earth System Science Data Discussions. doi: 10.5194/essd-2017-7

Forecast and warning concept for landslides in Switzerland based on rainfall triggering thresholds and multiscale hydrological modelling

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In Switzerland floods are responsible for most of the damage caused by rainfall-triggered natural hazards (89%), followed by landslides (6%, ca. 520 M Euros) as reported in Hilker et al. (2009) for the period 1972-2007. The prediction of landslide occurrence is particularly challenging because of their wide distribution in space and the complex interdependence of predisposing and triggering factors. The overall goal of our research is to develop an Early Warning System for landsliding in Switzerland based on rainfall forecasts and hydrological modelling. The system will use meteorological forecasts from Numerical Weather Prediction (e.g. COSMO) of radiation, temperature, precipitation etc. and estimate the wetness of the soil at a resolution of 1-2 km. The probability of landsliding will then be estimated through rainfall thresholds and/or slope stability modelling. In the latter case, large scale soil wetness will be redistributed to local soil moisture states applying topographic methods, reaching a resolution appropriate for stability assessment (ca. 20-100 m).

In the first stages of the project, we focused on the development of a framework for the definition of rainfall thresholds. We analysed rainfall triggering thresholds for landslides from a new gridded daily precipitation dataset (RhiresD, MeteoSwiss) for Switzerland combined with landslide events recorded in the Swiss Damage Database (Hilker et al.,2009). The high-resolution gridded precipitation dataset allows us to avoid problems of colocation between raingauges and landslides which has been a limitation in many previous studies.

Each of the 2272 landslides in the database in the period 1972-2012 was assigned to the corresponding 2x2 km precipitation cell based on its location. For each of these cells, precipitation events were defined as series of consecutive rainy days and the following event parameters were computed: duration (d), maximum and mean daily intensity (mm/d), total rainfall depth (mm) and maximum daily intensity divided by Mean Daily Precipitation (MDP). The events were classified as triggering or non-triggering depending on whether a landslide was recorded in the cell during the event. This classification of observations was compared to predictions based on a simple threshold model for each of the parameters. The predictive power of each parameter and the best threshold value were assessed by ROC curve analysis and statistics such as AUC and True Skill Statistic (TSS).

Event parameters containing intensity were found to have similarly high predictive power (TSS=0.54-0.59, AUC=0.85-0.86), with the exception of duration (TSS=0.24 and AUC=0.65). Slightly better performances were obtained when considering a typical power law intensity-duration curve (TSS=0.6). The analysis was repeated for sub-regions of the country based on erosivity and climate, using local climate (MDP) and erodibility (Kuehni and Pfiffner, 2001), or a combination thereof, in the classification. When defining regional maximum intensity thresholds, the performances were further improved in all cases: for erodibility (TSS +1.3%), for MDP (TSS +3%), and for a combination of the two (TSS +5.1%). The regional maximum daily intensity thresholds varied greatly among classes,

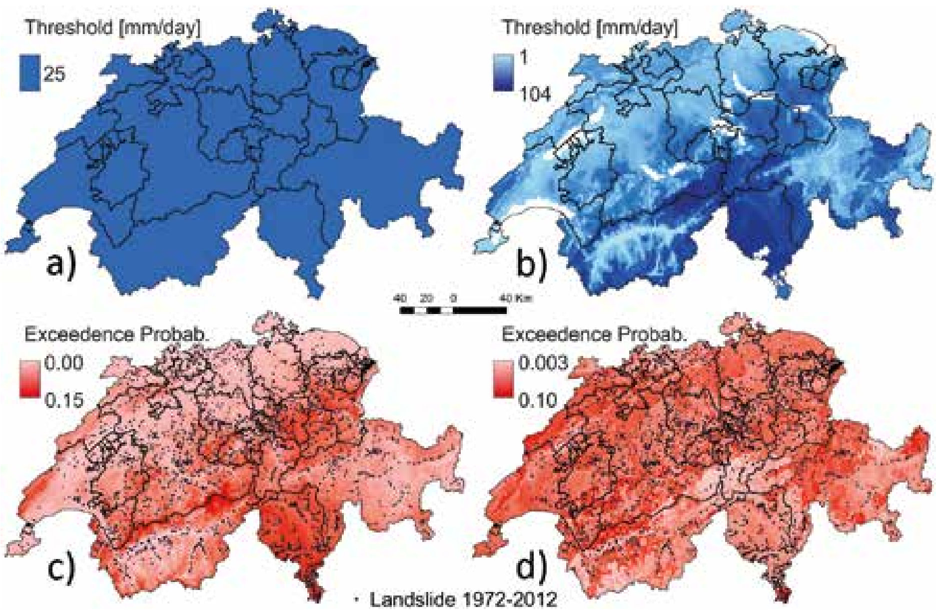

Figure 1: Best rainfall thresholds and the correspondent exceedance probability computed for 1972-2012. The recorded landslides are shown as black dots. a) best country-wide maximum daily intensity threshold, c) corresponding exceedance probability, b) best threshold computed using local Mean Daily Precipitation and best maximum intensity/MDP thresholds for each of the 16 MDP-erodibility region and d) the corresponding exceedance probability.

with differences of up to 43 mm/day, and they increased with decreasing erodibility and increasing wetness (MDP). The range of best threshold values are even greater when considering variables divided by the local MDP value (Fig.1, for maximum daily intensity). The trend of increasing thresholds required to generate landslides in wetter climates suggests the existence of a landscape balance between climate, erosion and soil formation. In order to demonstrate the quality and robustness of the results, we also analysed ROC reference cases obtained by randomization of landslides in space and time, and resampling to equal sample size between triggering and non-triggering events (prevalence).

From these preliminary results, we conclude that the rainfall threshold identification method defined here is robust, the True Skill Statistic is an adequate optimization criterion for the definition of rainfall thresholds, and that erodibility and local climate (Mean Daily Precipitation) provide additional information with predictive skill for landslide generation. With the goal of further improving performance, we now plan on including soil moisture as an antecedent condition and increasing the temporal resolution by utilizing hourly rainfall. This will allow us to capture strong convective events, missed at the daily timescale.

GPU accelerated BASEMENT enabling Monte-Carlo simulations for flood risk analysis

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One application within the wide field of applications for Shallow Water Equations (SWE) is flood risk analysis. Thanks to recent advances in numerical methods solving the two-dimensional SWE, highly accurate and robust numerical schemes are at disposal. In addition high resolution data is usually available for representing the topography in SWE models. Generally, the limiting factors for accuracy in flood models are existing uncertainties in the definition of boundary conditions (e.g. inflow hydrograph) and closure relations (e.g. bottom friction). To incorporate these uncertainties into impact assessment of the flood prone area, the propagation of the uncertainties through the computational flood model has to be established. One option to achieve this is the method of crude Monte-Carlo (MC) simulation. To be applicable in practice this method requires highly efficient evaluations of the computational model.

The numerical code BASEMENT (Basic Simulation Environment) is solving the SWE equations, e.g. answering questions concerning flood risk analysis. For reasons of flexibility and accuracy the SWE are solved here on unstructured grids. To improve the computational performance of BASEMENT and therefore enabling the possibility MC simulations in high resolution flood applications, its numerical kernel was heavily parallelized following the concept of Gustafson's law of data parallelism. To this end the numerical kernel of BASEMENT was embedded into OP2, which is an open-source framework for the execution of unstructured grid applications. By source-source translation OP2 generates appropriate back-end code for the different target platforms (clusters of GPUs or multi-core CPUs) by introducing an additional level of abstraction between the numerical model and the actual implementation of the parallelized code.

First tests show promising results: a speedup of more than two orders of magnitude was reached for large problems running on affordable general purpose Graphic Processing Units (GPU). This allows for MC simulation in a broad range of applications. As an example of successful uncertainty propagation the proba-

bilistic flood map induced by a hypothetical dam break scenario of an embankment dam is shown in Figure 1. It is obtained by routing 3000 possible dam breach hydrographs downstream to the flood prone area within 60 hours of simulation. In this application the mesh consists of roughly 200'000 computational cells and the real time is 12 hours, resulting 75 seconds per model evaluation in average.

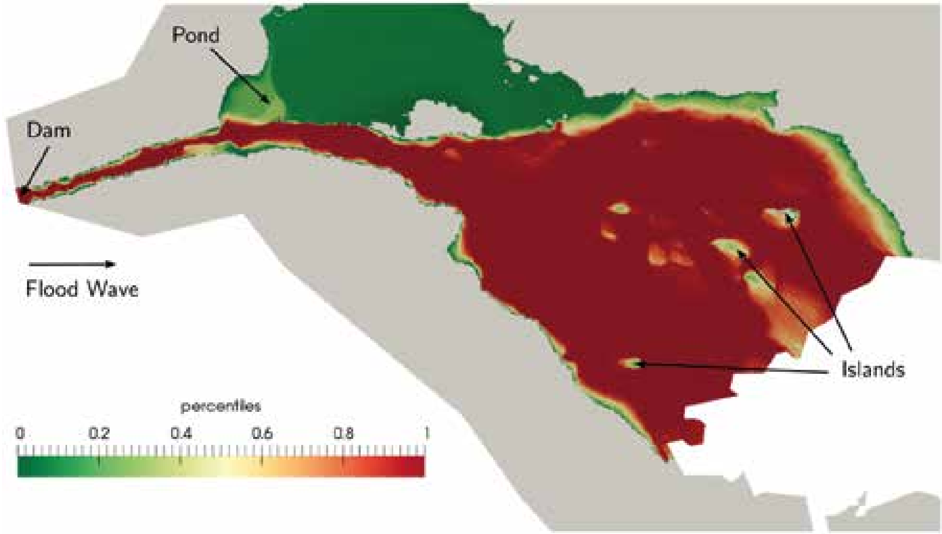

Figure 1: : Probabilistic flood map showing the probability of flooding across the flood prone area: triggered by a hypothetical dam break, generated by 3000 flood wave simulations, using GPU accelerated BASEMENT.

Terrestrial remote sensing of glaciers using laser scanning and radar interferometry

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Laser scanning and radar interferometry both allow measuring surface changes of glaciers remotely with areal coverage. Instruments for terrestrial instead of airborne or satellite-based use theoretically enable change detection on the sub-millimeter to centimetre level with the instrument set up at a distance of several kilometres from the glacier. Measurements are made at different times, possibly only a few seconds to minutes apart, and the analysis yields changes during the respective interval. While both technologies originally yield data representing the respective average distance and reflectivity of a large number of surface segments illuminated by the instrument and may thus appear equivalent, the resulting data differ vastly in terms of information content, spatial resolution, and dominant sources of uncertainty. The technologies are therefore complementary.

Terrestrial radar interferometry uses frequency modulated microwaves to measure amplitude and phase changes of reflected signals over time. Using antennas with small physical dimension and applying the synthetic aperture principle, or using large antennas and rotating them, a space of some tens of degrees up to 360° (in case of rotating antenna) horizontally and about 60° vertically can be covered. The raw results are estimates of displacements along the line-of-sight or look direction from the radar instrument to the monitored surfaces. Due to the working principle of the radar interferometer the object space is represented in terms of azimuth/range bins typically 4-8 mrad wide and 0.5-0.75 m deep. The measurements have an internal precision of <1 mm but an accuracy which may be worse than several cm due to uncompensated atmospheric effects. They represent the respective weighted average displacement over the entire bin and may thus be very difficult to interpret, in particular if there are different unconnected surface parts in the same horizontal direction. However, if there is a single dominant reflector within such a bin and if the atmospheric phase screen can be estimated sufficiently well from a set of stable points of surface patches, the measurement represents the displacement of this particular reflector with mm- to sub-mm-accuracy.

Terrestrial laser scanning (TLS) uses amplitude modulated light (near infrared for glacier monitoring) to measure the intensity and time-of-flight of backscattered signals thus representing the average reflectivity and distance of the surface patch illuminated by the laser beam during one measurement. Typically the beam-width is on the order of 0.2-0.3 mrad, and the laser beam is rotated about two orthogonal axes in order to cover up to 360° horizontally, and up to 160° vertically. The precision of the range measurements corresponds to a few mm to cm per point, and the accuracy is on a similar level. Again, atmospheric effects have a strong impact, but they are less detrimental for TLS than for radar because of the significantly lower impact of humidity and because of the longer (modulation) wavelength in case of TLS. The raw results of TLS-based glacier monitoring are distance changes between the instrument and the glacier surface along specific spatial directions parameterized by horizontal and vertical angle.

While the accuracy of the raw TLS data may be much worse than that of the radar results, and furthermore, TLS requires clear line-of-sight while radar also works with fog and clouds, interpretation of the TLS results is much easier because of the clear link to individual spatial directions. Furthermore, TLS-derived point clouds represent the surface topography of the glacier such that it is possible to use distinctive geometric or radiometric features (e.g. crevasses visible in the point cloud) to determine 3D displacements between epochs. We have shown that it is also possible to use feature tracking within the radar amplitude images to derive displacement of distinctive surface features between different azimuth/range bins. However, both the features and their displacements must be very large because of the comparatively poor azimuth/range

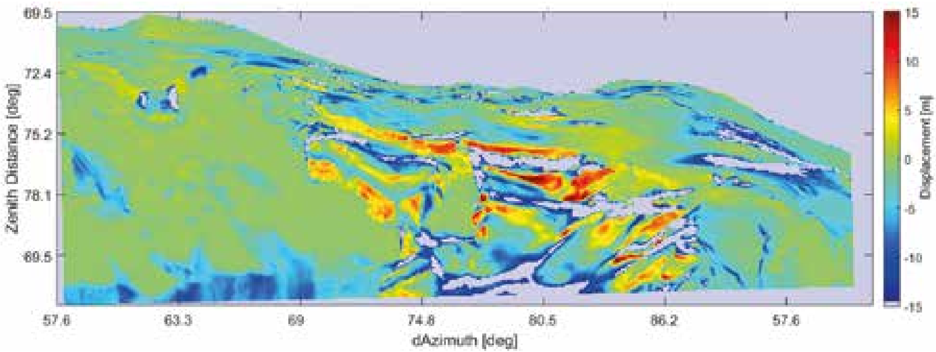

Figure 1: TLS-based LOS displacements of Weissmies glacier between April and September 2015

resolution of the radar. 3D displacements useful for glacier monitoring can hardly be obtained from the radar measurements.

Finally, there is a fundamental difference resulting from the fact that the radar yields differential displacements between measurement epochs while TLS yields absolute distances for the respective epochs. In order to determine surface changes over a longer time, e.g. a few months, the radar results have to be integrated in case of TLS just the difference between two measurements is needed. So, the accumulated displacements obtained from the radar results are affected by random-walk type noise, and additionally by errors due to temporary loss of coherence during the longer time. Large break-offs, snow accumulation due to precipitation, snow transport due to wind and similar effects are not or not entirely reflected by the accumulated radar results. The strength of radar interferometry is yielding highly accurate average displacement rates over short time spans (several hours to a few days) while the strength of TLS is to yield accurate absolute changes over longer time intervals.

In this presentation we highlight the strengths and weaknesses of both technologies, along with the related research carried out by the professorship in geosensors and engineering geodesy. We use data obtained at the Bis glacier and at the Weissmies glacier in Switzerland as examples.

Seismic monitoring of the 2016 outburst flood of Lac des Faverges on Glacier de la Plaine Morte

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Glacier de la Plaine Morte located in Switzerland's canton Bern is the largest plateau glacier in the European Alps. It covers a narrow elevation range and is extremely vulnerable to climate change. During snow melt, it feeds three marginal lakes that have experienced sudden subglacial drainage in recent years, thereby causing flooding in the Simme Valley below. Of greatest concern is Lac des Faverges at the southeastern end of the glacier that has drained near the end of July in recent years, with flood levels reaching capacity of flood control systems downstream. The lake levels are carefully monitored but precise prediction has not yet been achieved.

In summer 2016, we monitored Lac des Faverges using passive seismological recordings combined with surface ice flow measurements. Seismology provides continuous measurements and has shown to provide valuable insights into englacial fracturing, basal motion of the ice and water flow through or under glaciers. Compared to other methods such as borehole studies and active geophysical methods, glacier seismology is advantageous in the sense that it provides spatial insight into the ice, allows monitoring on seasonal scales and requires relatively little maintenance.

In the search for precursory ice fracturing to the lake drainage to improve forecast, four seismic arrays comprised of five short-period borehole seismometers as well as fifteen 3-component geophones were installed on different portions of the glacier and collected continuous seismic data for several months. Furthermore, we use this station configuration to study the temporal evolution of the subglacial drainage system by analyzing water-flow generated seismic tremors.

Compared to previous recent years, the 2016 outburst flood of Lac des Faverges occurred unusually late on August 27 after the lake volume reached an all-time maximum of roughly 2 Mm^3 (million cubic meters). Half of this volume drained within approximately ten hours after the drainage initiation, the complete drainage lasted for six days. We find that the lake drainage was associated with numerous fracturing events and strong water tremors (Fig. 1). Showing no noticeable seismicity before, we detected considerable icequake activity in the lake's vicinity emerging several hours prior to the drainage onset. This suggests the presence of hydrofracturing in the initiation stage of the outburst flood. Regarding water tremors, we notice a strong correlation between tremor amplitude and melt/lake-water discharge especially after the drainage process. We interpret this as the transition from an inefficient distributed to an efficient and channelized drainage system introduced by the opening of subglacial conduits during the outburst flood.

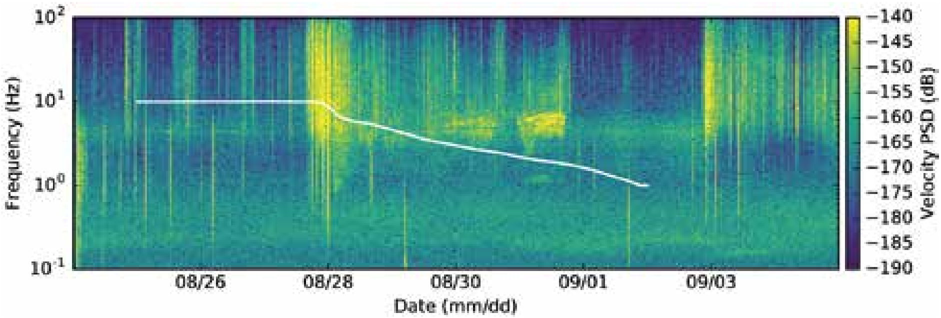

Figure 1: Vertical ice vibration power spectral density recorded by a seismic station installed a few hundred meters from the drainage moulin. High frequency vertical yellow bands represent icequake activity (fracturing), the horizontal band centered around 5 Hz is caused by turbulent water flow and resonance effects. The white line indicates the lake level.

Quantifying avalanche protection in forests using remote sensing

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Mountain ecosystems provide a broad range of benefits to society, such as climate regulation, recreation, habitat services, and protection from natural hazards. Spatially explicit assessments of these ecosystem services and the trade-offs between them are an important tool for decision makers in ecosystem management and spatial planning, and remote sensing is a promising source of data for such assessments.

In alpine regions such as Davos, avalanche protection is a particularly important service provided by mountain forests. The probability of an avalanche releases is significantly decreased in forested areas, and when an avalanche flows through a forest, some of the snow is detrained behind trees. This effect reduces the total mass of the avalanche flow, and can be quantified in a new version of RAMMS. The capacity of forests for avalanche prevention and detrainment depends on their structure, in particular their density and species composition. We use LiDAR data to measure canopy cover as a proxy for forest density, and an object-based random forest classification using a combination of airborne CIR images, LiDAR, and Sentinel2 to classify evergreen and deciduous forests. On the other side, the demand for avalanche protection depends on the risk to human life and infrastructure, and can be mapped using building extraction from LiDAR.

To integrate the various types of data, models, and expert knowledge required to model avalanche protection, we use a Bayesian Network approach. Bayesian Networks are directed graphs with an underlying joint probability distribution, where the nodes represent variables, and the links describe causal relationships between them. The individual links can be quantified independently, and the graphical representation facilitates communication about the system. The probabilistic nature of the network allows us to quantify the uncertainty at different steps within the model.

We map the provision and demand for avalanche protection in the Dischma valley. Additionally, we analyse the uncertainty in our assessment. Overall, a large part of the uncertainty in the avalanche protection model comes from the variability in release conditions. There is some uncertainty in the EO-based classification of forest structure, particularly in the heterogeneous stands near the tree line. Elsewhere, the uncertainty in potential ES provision is largely due to the links between ecosystem structure and function, demonstrating the need for a better understanding of the protection functions.

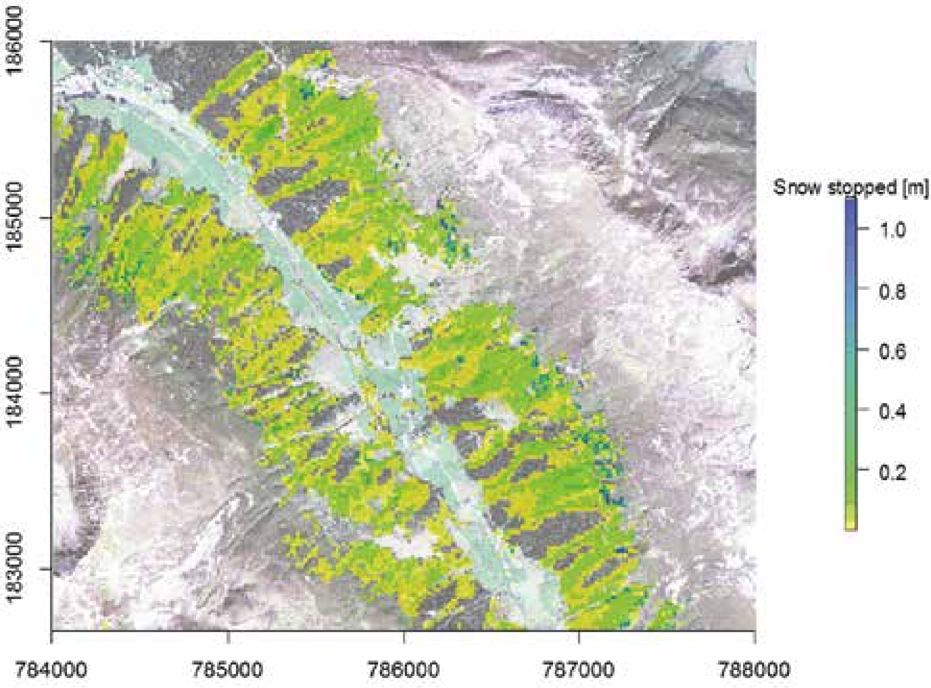

Figure 1: Map showing the modelled avalanche protection function (expressed as height of snow stopped per pixel) of forests in the Dischma valley, Davos.

Flow regulation effects on riparian vegetation: the Maggia case

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In a context of increasing energy demand, hydropower is currently the leading renewable energy source, accounting for about 16% of the global production of electricity with just minor greenhouse gas emissions. However, the benefits of hydropower production are counterbalanced by human modifications, such as damming and water abstraction, which pose threats to countless natural systems, including riverine floodplains, the importance of which is widely recognised both in terms of ecosystem services and supported biodiversity.

Alpine rivers in Europe are particularly threatened because they have been massively channelized for flood protection, their flow is often regulated by dams and their bed gravel has been used as a resource. This concurrence of conditions led to the disruption of river-aquifer flow interactions, a lateral disconnection of floodplains and the disturbance of sediment fluxes. The prediction of the impact of such changes on the ecology of rivers requires a combined effort of numerical modelling and field observations, which is to date missing.

This research intends to simulate the response of river and groundwater systems to different environmental flow strategies and to quantify the effects of such response on riparian vegetation growth and spatial distribution. To this purpose, specifically designed numerical models of river-aquifer flow interactions and of their impact on riparian vegetation growth in a heavily regulated Alpine gravel bed braided river will be used. The modelling tasks will be supported by real life measurements collected by several instruments installed on the field. This will allow to quantify the combined effect of water stress by floods and by droughts on the dynamics of riparian vegetation, in terms of its growth and spatial distribution.

The Maggia valley, located in Canton Ticino, will be taken as a case study for the development, calibration and validation of the models to be employed for the simulations. The Maggia floodplain is a particularly suitable site, since the flow of the Maggia river is regulated by hydropower dams and riparian vegetation, the growth of which can be conveniently monitored, is present on the gravel bars along the floodplain with a natural dynamic. Vegetation distributions have been

quantified from aerial photography since the pre-dam period, and presently vegetation growth is monitored by a terrestrial camera system at the river reach scale and a dendrometer network at the individual tree scale.

In order to analyse the effects of new flow regimes on riparian vegetation, sophisticated numerical tools will be needed for simulating the three main areas involved in this research: surface water, groundwater and riparian vegetation dynamics. On the one hand, an existing coupled surface-subsurface hydraulic model is being improved by testing and validating its performance for long term simulations and individual flood events in the Maggia, as well as by enhancing its capability of reproducing the complex set of processes describing the interaction between surface water and groundwater. On the other hand, the improved hydraulic model will be interfaced with a riparian vegetation model, in order to analyse the impacts of streamflow regulation due to hydropower systems on the plant growth in the floodplain.

Additionally, the outcomes of the coupled model will be validated by means of measurements obtained from instruments that have been installed so to monitor the aquifer fluctuations and the growth of vegetation under water stress conditions. Several devices (including piezometers, thermometers, electrical

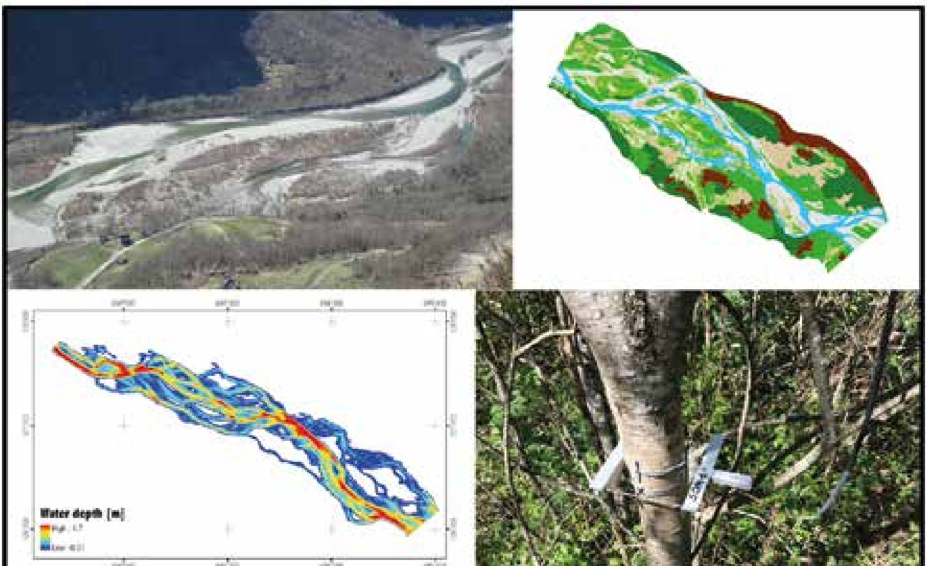

Figure 1: The Maggia floodplain and some numerical and experimental analyses thereof.

conductivity sensors, cameras with visible and infrared sensitivity, dendrometers and weather stations) have been or will be installed at selected locations in the Maggia valley; they will provide real life variables to be used as benchmark values for testing the performance of the models.

Among the expected results of this research, it is foreseen that: a) an improved surface water – groundwater coupled model will be obtained, able to accurately simulate river-aquifer exchange fluxes in a braided Alpine stream, also accounting for land processes (evapotranspiration) and dynamics in the hyporheic zone, and capable of long-term simulations at the river corridor scale; b) the coupling of such model with a riparian vegetation model will be accomplished, allowing to estimate the water stress of riparian species in regulated streamflows and their response to environmental flow policies; c) a model-based quantitative assessment of how riparian species respond to different flow conditions, as well as to new minimum flow release strategies, will be achieved.

The result of this research will prove to be a valuable tool for a fine adjustment of environmental releases in the Maggia valley, improving impacts on the riparian ecosystem with a reduced water diversion at the same time, and it will aid river restoration actions in other Swiss Alpine rivers, which aim to restore or maintain natural dynamics in riparian vegetation downstream of dams.

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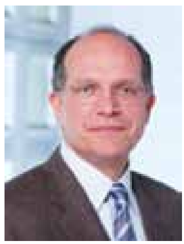

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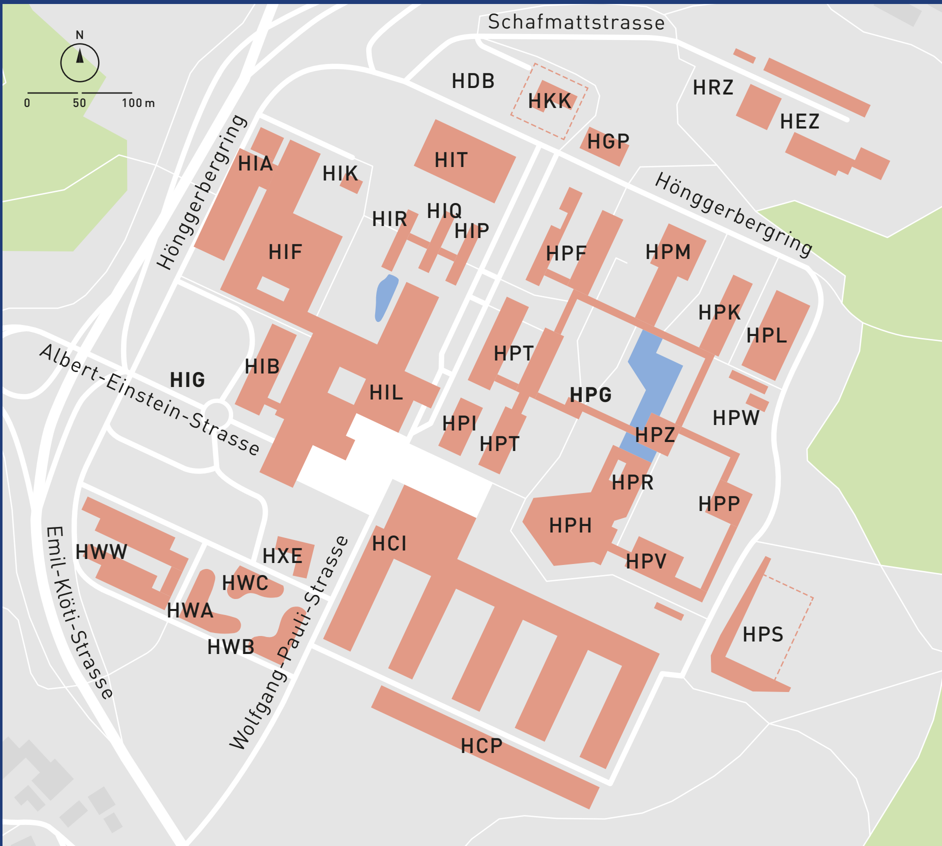

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